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A Comparison of Pyrethrum Fogging and Screen-sweep Netting of Micro-Hymenoptera in Southern California Chaparral

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Abstract.—Three chaparral plant species, *Adenostoma fasciculatum* Hook. and Arn. (Rosaceae), *Ceanothus megacarpus* Nutt. (Rhamnaceae) and *Quercus berberidifolia* Liebm. (Fagaceae), were sampled for micro-Hymenoptera in the Santa Rosa Plateau Nature Reserve in Southern California. Two sampling methods of the shrub's canopy are contrasted: screen-sweep netting and pyrethrum fogging. Using both sampling methods and across all of the plant hosts, 242 species of Hymenoptera were collected. A total of 558 individuals and 173 species were collected by fogging, and 287 individuals and 115 species by screen sweeping. Although fogging captured more individuals and species, results were significant only for the number of individuals collected on *Quercus* and number of species on *Adenostoma*. On the three different plants, fogging sampled a similar or greater number of species than did screen sweeping. In terms of estimating species richness, fogging had an equivalent or greater efficiency than sweeping for collecting individuals and species. When combined with the labor efficiency involved in processing field samples, fogging is superior to screen sweeping. However, given the sample sizes within this study, both techniques are necessary, with the fogging technique sampling only 71.5% of the total number of species of Hymenoptera.

Hymenoptera are one of the most diverse groups of insects, with approximately 115,000 described species and 300,000 to 2.5 million undescribed species (LaSalle and Gauld 1992, 1993, Gauld and Gaston 1995, Stork 1988, Grissell 1999). Based on conservative estimates, more than 10 percent of all insect species are parasitoids, and approximately 75% of these are Hymenoptera (Eggleton & Belshaw 1992). Recent estimates for Chalcidoidea alone estimate 357,000–400,000 species, of which only about 22,000 have been described (Noyes 1978, Noyes 2000, Heraty and Gates 2003). Parasitic Hymenoptera are valuable to agriculture as biological control agents (Van Driesche and Bellows 1996) and to conservation as a means of measuring biodiversity and a potential indicator of the diversity of lower trophic levels (Kremen et al. 1993, Heraty and Gates 2003). Many of these parasitoids are small, usually ranging in size from 1–5 mm, and difficult to collect except with specialized methods (Noyes 1982, Noyes 1989). Various authors have attempted to evaluate the best methods to sample these micro-Hymenoptera with an emphasis on both numbers of individuals and species (Masner and Goulet 1981, Darling and Packer 1988, Noyes 1982, Noyes 1989, Buffington and Redak 1998).

Many studies have compared collecting techniques for Hymenoptera in tropical and temperate ecological regions (Henderson and Whitaker 1977, Noyes 1989, Gadagkar et al. 1990, Erwin 1995, Hill and Cermak 1997, Longino and Colwell 1997, Stork and Hammond 1997, Hoback et al. 1999, Yanoviak 2003), but little has been written about sampling in the short, dense, scrub vegetation that is typical of Mediter-

ranean climate zones. Use of an "Allen Vac" in a coastal sage scrub plant community in Southern California produced more individuals and a higher diversity of Hymenoptera than did sweep netting, and was considered more effective because insects were sampled from deeper within the shrub canopy than possible for a sweep net (Buffington and Redak 1998). The primary disadvantage of vacuum sampling is the damage caused to small, fragile parasitic Hymenoptera, which can make identifications difficult. Another important aspect for choosing a particular method is the amount of time spent sorting through the accumulated debris to find specimens (Southwood 1978). The efficiency of vacuum sampling is counterbalanced by the labor necessary to sort specimens from the accumulated debris collected along with the specimens. Unfortunately, sweep netting and the direct aspiration of minute specimens is probably the least efficient method of sampling – many specimens may simply escape during collection, avoid detection in the accumulated plant debris, or may not be sampled if they are not readily accessible by the net. Adding a metal screen to the net opening to exclude debris (Noyes 1982) can increase the efficiency of finding specimens, but this can result in greater damage to the specimens, and the efficiency of processing will depend on whether specimens are aspirated (maximizing loss of specimens) or if the entire sample of specimens and plant debris is collected into alcohol and later sorted in the laboratory (maximizing processing time). To improve the quality of specimens and reduce the time spent sorting, new methods for rapid assessment of Hymenoptera populations, and especially micro-Hymenoptera, in dense canopy situations are needed. Possible solutions include passive collecting techniques such as Malaise trapping (indirect method), pan trapping (indirect), or insecticide fogging techniques (direct method). These techniques yield fewer damaged specimens and a limited amount of debris, but only the latter can be used to selectively sample specific plant hosts, as explained herein.

Canopy fogging techniques were reviewed by Erwin (1989), who noted that such techniques allow for sampling of tropical and temperate forest canopies more effectively than with other methods such as sweep netting. Problems with fogging in a tree canopy include collecting insects outside of the sampling area, drift of specimens from within the sampling area, and the need to collect at dawn, when there is no breeze, but perhaps less insect activity (Erwin 1989, Stork and Hammond 1997). Importantly, insects are collected somewhat randomly and can be sampled in replicated samples for a specific area (Stork and Hammond 1997). Insecticide fogging can also be applied to collecting insects on rough or inaccessible surfaces such as tree trunks (C. Burwell, pers. comm.) or vertical rock faces (S.B. Peck, pers. comm). In a chaparral vegetation community, the issue is not whether sweeping can reach the upper canopy, but whether sweeping can efficiently and thoroughly sample insects from within the interior of the 'canopy' of dense, often thorny, bushes. Insecticide fogging of this miniature tree canopy has a potential for sampling a different array of insects in both numbers and species than would be sampled by beating the exterior of the shrub with an insect net. Canopy fogging is also an easily quantifiable method since a known surface area of catch basins can be put underneath the canopy being fogged. Canopy fogging in chaparral ecosystems might also produce samples that are free of debris or damage unlike screen-sweep netting. Another attribute of fogging is that it allows for the collection of specimens from individual plant species like screen-sweep netting. In this paper we hope to test the efficacy of pyrethrum fogging compared to screen-sweep netting in a chaparral ecosystem in Southern California for collecting parasitic micro-Hymenoptera.

Fig. 1. Fogging method used to collect Hymenoptera from a *Quercus berberidifolia* bush in Southern California.

MATERIALS AND METHODS

Location and date.—Sampling took place on the two dates July 11, 2001 and July 18, 2001 at 3 adjacent sites in the Santa Rosa Nature Preserve, in Riverside County, California, at 33 31′N 117 14′W and 590 m elevation. We chose 3 similar stands of dense chaparral over a 5-acre area: one stand adjacent to a field of endemic bunch grass, the second adjacent to a road bordered by invasive grass, and the third in the heart of a dense stand of chaparral. We used both fogging and screen sweeping to collect from 3 individual bushes from 3 dominant plant species on two dates: *Adenostoma fasciculatum* Hook. and Arn. (Rosaceae), *Ceanothus megacarpus* Nutt. (Rhamnaceae), and *Quercus berberidifolia* Liebm. (Fagaceae).

Screen-sweeping.—We used a triangular net hoop with 38-cm sides and a recessed covering of 6.4-mm hardware cloth to exclude large debris. The sweep net was a fine-meshed net bag from Bioquip (Gardena, CA), with the apex of the net bag open and held closed by a twist tie that could be removed to empty the contents into a 1-quart plastic Ziploc® bag containing 80% EtOH. The contents of the Ziploc® bag were rinsed with additional 80% EtOH to kill and preserve the insects. Each bush was swept over all its of the surfaces by a single collector (John Pinto, UCR) to keep the sampling as uniform as possible. Sampling of all 3 sites took about 45 min on each date.

Fogging.—The insecticide fogging of shrubs required several steps on the two dates. First, 36 yellow Dixie® bowls (total area = 1 m^2) were placed underneath the canopy of each bush to be sampled. Each bush was sprayed with Raid Yard Guard® for 1 min from a distance of about 1.5 m, enveloping the bush in a fine fog with no visible droplets on the leaves (Fig. 1). Approximately one spray can (473 ml; 16 fl oz) was used for 3 bushes. After 5 minutes, pans were emptied and rinsed with 80% EtOH into one gallon plastic Ziploc® bags. Fogging took approximately

2 hours to complete from setup to finish for all 3 sites. The air movement was minimal during sampling periods and was not considered to have impacted specimen drift.

Processing samples.—Two strainers with square mesh openings of 3.2 and 1.6 mm were used to separate the screen-sweep samples into course, medium and fine debris samples. Because of the lack of debris, fogging samples were directly sorted without screening. Each sample was sorted with use of an 11×11-cm Rose Entomology® sorting tray with parallel sorting lanes separated by raised ridges 13-mm apart. To ensure that all specimens were discovered in the samples, each tray was sorted twice, and in some screen-sweep samples three times. Specimens were transferred to small glass vials and then dried for mounting by use of the Hexamethyldisilizane (HMDS) technique (Heraty and Hawks 1998) and then card mounted (Noyes 1982). All mounted specimens were individually labeled with collection information and a unique specimen identifier number. Data were input into a Filemaker® database for the UCR Entomology Research Museum, where all material was deposited. All Hymenoptera were identified to family, genus, and morphological species groups using available identification keys. Certain groups were identified, or our identifications verified, by other local specialists at UCR: Mymaridae identified by Serguei Triapitsyn, Trichogrammatidae by John Pinto, Pteromalidae and Eulophidae by Roger Burks, Signiphoridae by James Munro, Figitidae by Matthew Buffington, and Aphelinidae by Jung-Wook Kim.

Data analysis.—ANOVA analysis revealed no significant difference in specimens collected between sampling dates ($p<0.05$), so we pooled the data for the remaining analysis. A 2-tailed Student's *t*-test was used to compare the number of individuals collected by fogging and sweep netting for each family (Mendenhall et al. 2003), the number of individuals in the two higher taxonomic groups (Chalcidoidea and non-Chalcidoidea) and families of Hymenoptera (Tables 1–3).

The ecological modeling program EstimateS version 7.0 (Colwell 2004) was used to compare the two methods for species richness (Figs 1–3) and similarity of shared species (Table 4) for Chalcidoidea and non-Chalcidoid micro-Hymenoptera by plant species. The diversity settings for EstimateS 7.0 were set to sample with replacement and the number of replications set to 1,000 to calculate the Chao1 richness estimator (Chao 1984), Sobs estimator (Colwell 2004) and singletons estimator (Chazdon et al. 1998, Colwell and Coddington 1994) (Figs 2–7). The advantage of estimating the diversity by selection of samples with replacement is that estimator variance remains meaningful at the right hand end of the accumulation curve, and thus can be used to compare data sets (Colwell 2004). Scatter plots of these estimator values of species were plotted against the estimated number of individuals observed in pooled quadrat samples to construct models (Figs 2–7). The Chao1 species estimator is used for the sampling history of species represented by at least two individuals (Magurran 2004). The Sobs estimator estimates sampling of the mean number of new species collected among the samples (Colwell 2004). The Singletons estimator estimates sampling of the mean number of new species represented only by one individual (Colwell and Coddington 1994), and thus is a rough estimate of the number of rare species. Accumulation curves from each of these estimators can be used to compare the relative efficiency of fogging and screen sweeping in capturing species diversity (Figs 2–7).

A Morisita-Horn species similarity index was calculated with use of standard default settings of EstimateS to compare the number of shared species collected on their respective plant species with fogging and screen sweeping after correcting for

Table 1. Mean number ± standard error (SE) (range and no. collected) of micro-Hymenoptera and morphospecies collected by fogging or sweep netting techniques at the Santa Rosa Reserve, California.

Plant type	Number of individuals		Number of species	
	Fog	Sweep	Fog	Sweep
	Total micro-Hymenoptera		Total micro-Hymenoptera	
Adenostoma	9.11±0.84 (3–18, 166)	4.61±0.19 (0–12, 82)	6.28±0.55* (2–11, 78)	3.61±0.51* (0–7, 40)
Ceanothus	6.56±1.16 (0–18, 117)	4.72±1.20 (0–18, 82)	5.39±0.75 (0–12, 56)	3.67±0.75 (0–13, 42)
Quercus	15.28±3.44* (0–46, 275)	6.89±0.96* (3–17, 123)	10.39±2.04 (0–28, 104)	6.00±0.82 (2–15, 67)
	Chalcidoidea		Chalcidoidea	
Adenostoma	5.67±0.66* (1–10, 102)	2.39±0.51* (0–7, 43)	4.7±0.53* (1–8, 52)	1.78±0.34* (0–5, 27)
Ceanothus	4.44±0.88 (0–9, 80)	3.83±1.09 (0–27, 69)	3.72±0.59 (0–9, 45)	3.17±0.98 (0–18, 31)
Quercus	11.11±2.65* (0–36, 200)	5.11±0.75* (0–12, 92)	7.28±1.55* (0–21, 71)	4.5±0.65* (0–11, 56)
	non-Chalcidoidea		non-Chalcidoidea	
Adenostoma	3.56±0.51 (1–9, 64)	2.17±0.58 (0–10, 39)	2.83±0.36 (1–6, 26)	1.61±0.38 (0–6, 13)
Ceanothus	2.06±0.35* (0–4, 37)	0.56±0.15* (0–10, 13)	1.78±0.28 (0–4, 11)	1.67±0.49 (0–9, 11)
Quercus	4.17±1.00* (0–15, 75)	1.72±0.34* (0–6, 31)	3.5±0.75* (0–10, 33)	1.56±0.26* (0–4, 11)

*Significant within a category (Student's *t*-test, $p<0.05$). Values for the same categories were not significantly different between the 2 dates pooled but are significantly different between plant hosts (GLM ANOVA, $p<0.05$).

Table 2. Number of species collected by each sampling method (pooled) and average number of individuals (x ± SE) of Chalcidoidea sampled at the Santa Rosa Reserve.

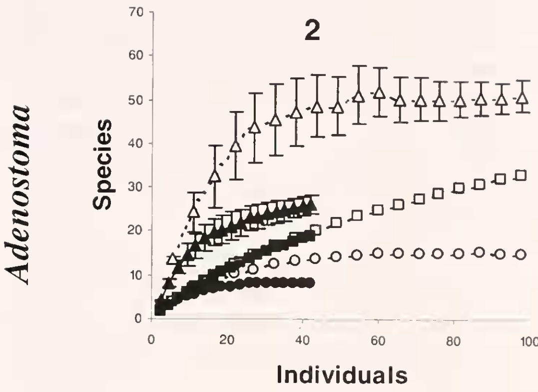
	Number of species			Mean no. of individuals	
	Fogging	Sweeping	Both	Fogging	Sweeping
Aphelinidae	13	5	4		
Adenostoma				0.90 ± 0.20* (16)	0.33 ± 0.18* (6)
Ceanothus				0.61 ± 0.23* (11)	0.28 ± 0.14* (5)
Quercus				1.28 ± 0.40* (23)	0.50 ± 0.17* (9)
Chalcididae	1	0	0		
Adenostoma				0	0
Ceanothus				0.06 ± 0.06 (1)	0
Quercus				0	0
Encyrtidae	23	9	2		
Adenostoma				0.67 ± 0.21 (12)	0.28 ± 0.18 (5)
Ceanothus				0.61 ± 0.22 (11)	0.33 ± 0.14 (6)
Quercus				0.50 ± 0.33 (9)	0.17 ± 0.09 (3)
Eulophidae	29	25	7		
Adenostoma				1.24 ± 0.29 (30)	0.78 ± 0.25 (14)
Ceanothus				0.67 ± 0.23 (12)	0.50 ± 0.23 (9)
Quercus				1.50 ± 0.50 (27)	1.33 ± 0.31 (24)
Eupelmidae	3	5	0		
Adenostoma				0	0
Ceanothus				0.11 ± 0.08 (2)	0.06 ± 0.06 (1)
Quercus				0.06 ± 0.06 (1)	0.22 ± 0.02 (4)
Eurytomidae	2	2	0		
Adenostoma				0.06 ± 0.06 (1)	0.06 ± 0.06 (1)
Ceanothus				0	0
Quercus				0.06 ± 0.06 (1)	0.06 ± 0.06 (1)
Mymaridae	3	1	11		
Adenostoma				0.61 ± 0.18 (11)	0.39 ± 0.14 (7)
Ceanothus				0.22 ± 0.10 (4)	0.33 ± 0.14 (6)
Quercus				1.17 ± 0.40 (21)	1.00 ± 0.29 (18)
Ormyridae	1	1	1		
Adenostoma				0	0
Ceanothus				0	0
Quercus				0.11 ± 0.08 (2)	0.11 ± 0.08 (2)
Pteromalidae	14	3	6		
Adenostoma				0.39 ± 0.14* (7)	0.11 ± 0.08* (2)
Ceanothus				0.28 ± 0.14* (5)	0*
Quercus				3.61 ± 1.19* (65)	0.67 ± 0.21* (12)
Signiphoridae	0	1	2		
Adenostoma				0.11 ± 0.08 (2)	0
Ceanothus				0.28 ± 0.11 (5)	0.44 ± 0.15 (8)
Quercus				0.89 ± 0.77 (34)	0.78 ± 0.29 (14)
Torymidae	0	3	1		
Adenostoma				0	0.11 ± 0.08 (2)
Ceanothus				0	0.06 ± 0.06 (1)
Quercus				0.06 ± 0.06 (1)	0.06 ± 0.06 (1)
Trichogrammmatidae	3	1	4		
Adenostoma				1.28 ± 0.39* (23)	0.33 ± 0.18* (6)
Ceanothus				1.61 ± 0.45 (29)	1.83 ± 0.64 (33)
Quercus				0.89 ± 0.30* (16)	0.22 ± 0.10* (4)
Chalcidoidea	92	56	38		
Adenostoma				5.67 ± 0.66* (102)	2.39 ± 0.51* (43)
Ceanothus				4.44 ± 0.88 (80)	3.83 ± 1.09 (69)
Quercus				11.11 ± 2.65* (200)	5.11 ± 0.75* (92)

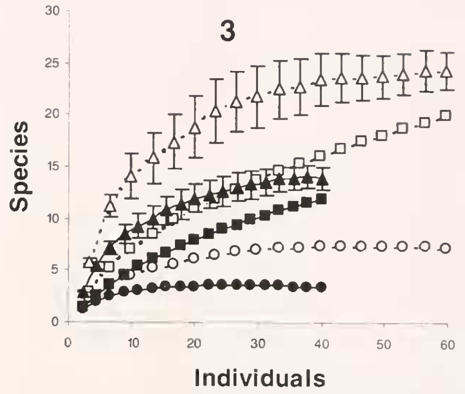
Table 3. Number of species collected by each sampling method (pooled) and average number of individuals (x + SE) of non-chalcidoid Hymenoptera sampled at the Santa Rosa Reserve.

	Number of species			Mean no. of individuals	
	Fogging	Sweeping	Both	Fogging	Sweeping
Bethylidae	1	0	0		
Adenostoma				0	0
Ceanothus				0.06 ± 0.06 (1)	0
Quercus				0.17 ± 0.09* (3)	0*
Braconidae	7	1	0		
Adenostoma				0.33 ± 0.19* (6)	0*
Ceanothus				0.50 ± 0.22 (9)	0.06 ± 0.06 (1)
Quercus				0.33 ± 0.14* (6)	0*
Ceraphronidae	6	1	2		
Adenostoma				0.44 ± 0.18 (8)	0.39 ± 0.16 (7)
Ceanothus				0.06 ± 0.06 (1)	0.06 ± 0.06 (1)
Quercus				0.17 ± 0.12 (3)	0.06 ± 0.06 (1)
Crabronidae	1	0	0		
Adenostoma				0	0
Ceanothus				0	0
Quercus				0.06 ± 0.06 (1)	0
Figitidae	3	1	0		
Adenostoma				0	0
Ceanothus				0	0
Quercus				0.17 ± 0.09 (3)	0.06 ± 0.06 (1)
Diapriidae	1	0	0		
Adenostoma				0	0
Ceanothus				0	0
Quercus				0.06 ± 0.06 (1)	0
Dryinidae	2	0	0		
Adenostoma				0.11 ± 0.08 (2)	0
Ceanothus				0	0
Quercus				0	0
Formicidae	6	0	4		
Adenostoma				0.56 ± 0.17* (10)	0*
Ceanothus				0.44 ± 0.15* (8)	0*
Quercus				1.28 ± 0.39 (23)	0.78 ± 0.13 (14)
Ichneumonidae	1	0	0		
Adenostoma				0	0
Ceanothus				0	0
Quercus				0.06 ± 0.06 (1)	0
Platygastridae	0	0	1		
Adenostoma				0.06 ± 0.06 (1)	0.28 ± 0.18 (5)
Ceanothus				0	0.06 ± 0.06 (1)
Quercus				0.11 ± 0.08 (2)	0.33 ± 0.20 (6)
Scelionidae	6	4	6		
Adenostoma				2.00 ± 0.46 (36)	1.50 ± 0.41 (27)
Ceanothus				1.00 ± 0.30* (18)	0.27 ± 0.11* (5)
Quercus				1.77 ± 0.55* (32)	0.50 ± 0.12* (9)
Sphecidae	1	1	0		
Adenostoma				0.06 ± 0.06 (1)	0
Ceanothus				0	0.11 ± 0.08 (2)
Quercus				0	0
non-chalcidoid Hymenoptera	35	8	13		
Adenostoma				3.56 ± 0.51 (64)	2.17 ± 0.58 (39)
Ceanothus				2.06 ± 0.35* (37)	0.56 ± 0.15* (10)
Quercus				4.17 ± 1.00* (75)	1.72 ± 0.34* (31)

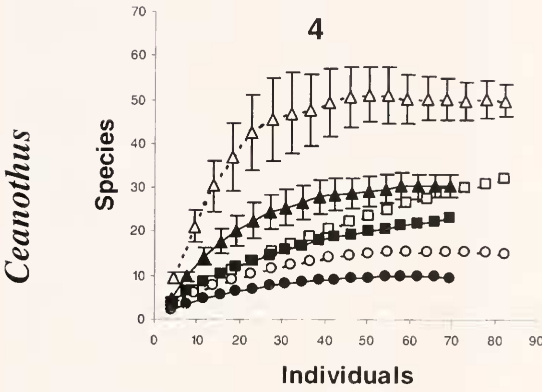
Chalcidoidea | **non-Chalcidoidea**

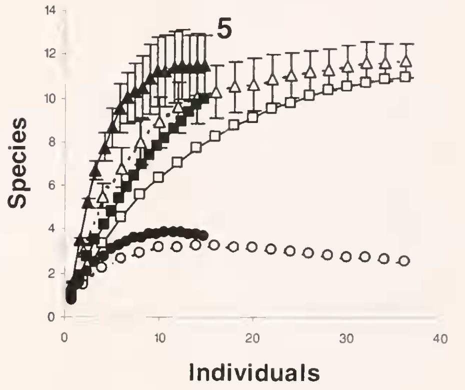
Adenostoma



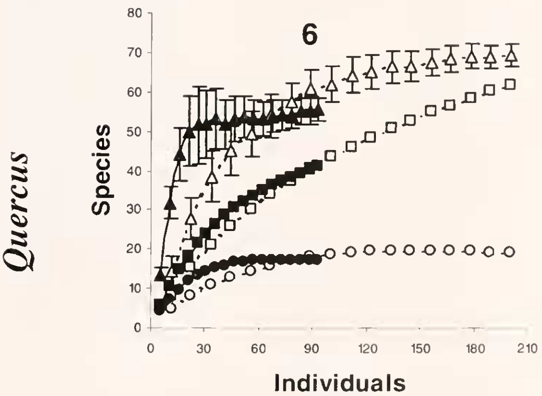


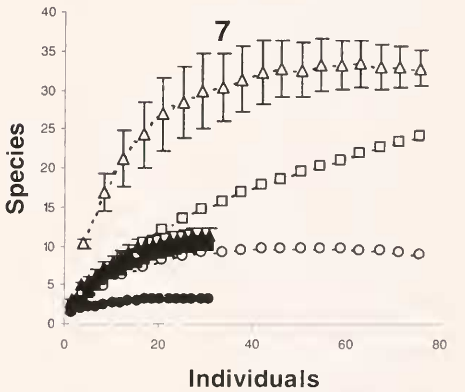
Ceanothus





Quercus





Figs 2–7. Species accumulation curves generated by use of EstimateS 7.0 for the pooled fogging (open symbols) and sweep-netting (closed symbols) data. Triangles represent the Chao1 estimator, squares the Sobs estimator, and circles the singletons estimator.

Table 4. Morisita-Horn indices for shared species of micro-Hymenoptera collected at the Santa Rosa Plateau Reserve by canopy fogging and screen netting by plant host.

	Chalcidoidea	Non-Chalcidoidea
Adenostoma	0.69	0.73
Ceanothus	0.84	0.59
Quercus	0.75	0.63
Total	0.84	0.77

sample size (Table 4). The Morisita-Horn index has been shown to be robust and more reliable than other shared species indices because it is not strongly influenced by species richness and sample size (Wolda 1981, Magurran 2004).

RESULTS

Fogging of the plant canopy consistently collected more individuals and species than screen sweeping across the 3 types of plants sampled (Table 1). A total of 558 micro-Hymenoptera specimens were collected by fogging as compared to 287 by screen sweeping. Samples were significantly different only for the number of individuals of all micro-Hymenoptera from *Quercus* and the number of species from *Adenostoma* (Table 1). More individuals of Chalcidoidea (Table 2) and non-Chalcidoid micro-Hymenoptera (Table 3) were collected with fogging across all plants sampled. Use of fogging produced significantly higher numbers of Chalcidoidea on *Adenostoma* and *Quercus* (Table 2) and non-Chalcidoid micro-Hymenoptera on *Ceanothus* and *Quercus* (Table 3) than sweeping. In virtually all of the family level comparisons, use of fogging produced a greater number of individuals than did sweeping (Tables 2, 3). However, the differences were significant for only some Chalcidoidea (Aphelinidae, Pteromalidae and Trichogrammatidae) and other Hymenoptera (Bethylidae, Braconidae, Formicidae, Scelionidae). Except for Pteromalidae on *Quercus*, Aphelinidae and Trichogrammatidae were the most commonly sampled wasps. Individuals of these families are minute and are likely most common in the interior canopy of the bushes where they attack sessile Hemiptera and eggs of various insects.

A total of 242 species of Hymenoptera were collected across all of the samples, with Chalcidoidea represented by 186 species (76.9%). For all species (micro-Hymenoptera, Chalcidoidea and non-Chalcidoidea), fogging consistently produced more species, on average, than screen-sweeping (Table 1) (173 versus 115 total species collected by each technique) and significantly more species on *Adenostoma* (Table 1). Significantly more species of Chalcidoidea were collected on *Adenostoma* and *Quercus*, whereas more species of non-Chalcidoidea were collected only on *Quercus* (Table 1). Each method did not always collect the same species. Only 38 species of Chalcidoidea and 13 species of non-Chalcidoid micro-Hymenoptera were sampled by both methods (Tables 2 and 3). Sweep netting collected an additional 56 species of Chalcidoidea (30.1%) and 8 species of non-Chalcidoid micro-Hymenoptera (14.3%) (Tables 2 and 3). As expected, because of the greater number of specimens collected fogging collected a larger proportion of additional species that were not collected by screen sweeping (92 species or 49.5% of Chalcidoidea; 35 species or 62.5% of non-Chalcidoid micro-Hymenoptera). When considering the unique species collected by a particular method, along with the species collected by both methods, fogging sampled 69.9% of the species of Chalcidoidea whereas screen sweeping sampled 50.5% of the species, and respectively 85.7% and 37.5% of the non-Chalcidoid micro-Hymenoptera. Because of different sample sizes obtained from each method (significantly more for fogging), an unbiased Morisita-Horn analysis estimated that the two sampling methods produced samples with 69–84% shared species of Chalcidoidea and 59–77% shared species of non-Chalcidoid micro-Hymenoptera (Ta-

ble 4). However, especially for Chalcidoidea, screen sweeping collected a large number of unique specimens (56) despite the low sample size.

Of the three estimators, Chao1 provides an indication of the ability to sample the species thoroughly (more than two individuals of each species sampled), Sobs focuses on the accumulation of new species, and the singletons estimator is the accumulation of species based only on a single specimen. Only the singletons estimator is expected to decline as a habitat is more thoroughly sampled and species are shifted to the Chao1 category. The Chao1 and Sobs estimates should both plateau as the number of species becomes thoroughly sampled. In all cases, estimates for fogging were consistently based on a sample with greater number of individuals (Figs 2–7; Table 1). Results for the Chao1 estimator species accumulation curve had the number of 'common' species both accumulate and also reach a plateau at a significantly faster rate using the fogging technique for most of the data partitions (Figs 2–4, 7), whereas screen sweeping accumulated common species at a faster rate for non-Chalcidoidea on *Ceanothus* (Fig. 5) and Chalcidoids on *Quercus* (Fig. 6). In these latter two cases, fogging still sampled more species overall on *Quercus* (71 versus 56), whereas the same number of species of non-Chalcidoidea (11) were sampled on *Ceanothus* and in neither case did the number of species appear to plateau (Figs 5, 6; Table 1). Thus fogging will generally sample the highest and best represented diversity of common species with the least effort, as based on the number of specimens collected. The mean number of new species accumulated (Sobs estimate) was virtually the same for Chalcidoidea using both methods (Figs 2, 4, 6), and for the non-Chalcidoid micro-Hymenoptera, slightly higher on *Ceanothus* (Fig. 5) or lower on *Adenostema* and *Quercus* (Figs 3, 7). The number of species represented by a single specimen (singleton) accumulated at a slightly faster rate in most of the fogging samples (Figs 2–4, 7), but were roughly the same for the *Ceanothus* non-Chalcidoidea (Fig. 5) and *Quercus* Chalcidoidea (Fig. 6). Only the non-Chalcidoid micro-Hymenoptera on *Adenostema* (Fig. 5) demonstrated a decline in the number of singletons, suggesting overall that the maximum number of species had been sampled even though the species accumulation curves (Chao1 and Sobs) had not yet reached a plateau.

DISCUSSION

Insecticide fogging of tree canopies has been experimented with since the late 1960's (Martin 1966, Gange and Martin 1968, Roberts 1973, Erwin and Scott 1980, Erwin 1983, Adis et al. 1984, Stork and Hammond 1997). Typical canopy fogging in the tropics is used to access the forest canopy 30–60 m above the ground (Erwin 1983, Stork and Hammond 1997). Here we suggest that the canopy of dense thorny shrubs in chaparral habitat can present some of the same problems of sampling, but on a much smaller scale. The fogging strategy employed in this paper has a number of advantages in: 1) relying upon compact and inexpensive equipment that can be carried easily to the field, 2) the sampling area can be defined by the collecting surface under the plant, 3) a specific bush or species of plant can be targeted, 4) debris is minimized and the specimens can be quickly and efficiently processed, 5) there is very minimal, if any, damage to specimens, and 6) there is no damage to the plants being sampled, which may be a factor in some conservation studies. Our method draws many parallels with the typical tropical forest canopy fogging as in Stork and Hammond (1997), and faces similar issues of specimen drift within and outside of the sampling area, but on a less dramatic scale. Climatic conditions (i.e. wind) remains an important factor, but can be monitored and controlled throughout the

sampling period, and sampling can be done during presumed periods of peak insect activity. Typical chaparral shrubs stand waist high and thus access to the canopy is not a problem, and fogging of chaparral or similar shrub canopies may allow access to this seldom collected niche.

Noyes (1989) demonstrated variable results when comparing sweep netting to canopy fogging of trees in the tropical forests of Sulawesi, but did not speculate as to which was more effective at collecting parasitic Hymenoptera. Noyes (1989) argues that each method of collecting will have its own advantages over another, but this may relate to sampling different ecological niches, more than the overall efficiency of collecting the same niche. We observed this within our study, in which fogging sampled only 71.5% of the Hymenoptera and screen sweeping sampling only 47.5%. A large number of species were represented by only one or two specimens, and the differential sampling may be due to a different distribution of species on the individual host plants being sampled. The only way to account for this would be to increase the number of plant hosts being sampled in order to decrease the variance in species being sampled; however, this would dramatically increase the effort for sampling with the screen sweep method.

In this study, insecticide fogging sampled a greater or equivalent number of individuals and species of micro-Hymenoptera as compared to sweep netting in a chaparral ecosystem (Tables 1–3, Figs 2–7). Similar to vacuum sampling, the difference was likely because of greater access to wasps within the interior shrub canopy (Dietrick et al. 1960, Buffington and Redak 1998). Sweep netting generally samples insects from the tops and sides of the shrub canopy (Southwood 1978, Buffington and Redak 1998). Differences in the shrub architecture may have led to some of the variability in the effectiveness of fogging versus screen-sweeping (Table 1, Figs 2–7). Both *Quercus berberidifolia* and *Adenostoma fasciculatum* have dense overhanging canopies that the screen-sweep net could not penetrate. However, *Ceanothus megacarpus* has a sparse willowy canopy architecture and the screen-sweep net could be used to sample most of the canopy. Thus, when sampling dense chaparral shrubs, canopy fogging would have an advantage over screen sweeping at capturing a greater diversity of micro-Hymenoptera. When sampling open shrubs, no difference in the wasps being sampled by either method is expected.

Insecticide fogging, coupled with the collection of specimens into pans of a defined size, allowed for better quantification of the capture of wasps in a defined area, with 1 m^2 being the combined area of the pan traps placed under each shrub. This is somewhat similar to the multiple 1 m^2 funnel sampling method employed in canopy fogging of tree canopies (Stork and Hammond 1997), although we did not treat each pan as a separate sampling unit because of the expected low sample size. Sampling by screen sweeping is more arbitrary, being based on the number of sweeps using an undefined arc, velocity, and the area sampled (Southwood 1978). It is possible to define the area sampled through screen sweeping by the size of the shrubs being sampled, which in this study certainly had a surface area greater than 1 m^2, but each shrub varied substantially in size. Other factors that mitigate against screen-sweeping are collector bias in sweeping efficiency and potential damage to the host plants by intensive sweep netting.

The efficiency of processing samples is an important factor. More time was spent in the field setting the pans under each shrub, fogging the canopy, and collecting specimens from the pans. However, the fogging technique produced samples almost entirely free of debris, which allowed

for specimens to be easily located and processed. Fogging could theoretically allow for more samples to be taken, which overall is the best way reduce the variance in samples from natural habitat (Southwood 1978).

It is difficult to compare trapping methods directly for numbers of individuals and species when, because of the method, they are not comparable for a similar investment of effort. Modeling of trap catches through various resampling methods allows for an estimate of whether the diversity and quota of specimens can reach the same asymptote, the relative efficiency of reaching that value, and whether a particular method has already reached that estimated value. In almost all cases, fogging was estimated to collect more species and at a faster rate than sweep netting (Figs 2–3, 5–7). Only on *Ceanothus* was the diversity of non-Chalcidoidea estimated to be equal and the number of species accumulated at a faster rate with screen sweeping (Fig. 5). The upright growth and open canopy of *Ceanothus* may allow for an equal number of individuals and species to be sampled by both methods. The Morisita-Horn shared species index (Table 4) indicates that the use of both fogging and screen sweeping sampled similar species of Hymenoptera (59%–84% similarity), with no bias in groups. Thus, when corrected for sample size either method would sample approximately the same groups of species in a chaparral ecosystem.

The goals of sampling parasitic Hymenoptera in different habitats are endless. Here we were interested in sampling numbers of individuals and species from isolated plants in a dense shrub canopy in chaparral habitat at a single point in time. This is a diverse ecosystem, with 242 species collected on only two sample dates. The same or more individuals were sampled from each plant using fogging as compared to screen sweeping. In terms of specimen quality, efficiency and quantification, insecticide fogging, with collection of specimens into circular pans placed under the shrub canopy, is a superior technique over both screen sweeping and vacuum sampling.

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